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Abstract

Project management often involves the selection of alternatives from various options for completion of one or more activities. In some cases in addition to uncertainty in cost and activity completion time, the reliability of the alternatives must also be considered. This situation often arises when alternatives involve new or unproven technologies or processes. In this research, we present a stochastic simulation-based optimization method to evaluate project networks to select from among alternatives for completing project activities when several options are available with stochastic completion times and reliability in terms of the likelihood of successfully completing the activity. The objective of this methodology is to optimize the expected time required to complete the project. The output of the method includes a distribution of the project completion time and the configuration of alternatives selected to complete the project.

Keywords
Project management, optimization, simulation, Reliability, Technology

1. Introduction
Project management has been used widely in the fields of engineering, product development, construction, information technology etc. (Ingason & Shepherd, 2014). Completing and delivering a project within the given deadline, budget, and quality is a very difficult task for project managers. While planning or executing a project, project managers are often faced with situations where the project may not meet the deadline unless additional action is taken. The project management literature provides a number of potential alternatives to consider for getting a project back on track including crashing activities, expanding the pool of resources, etc. One of these potential alternatives may be to consider a different method or technology to complete an activity. In some cases, the alternative method or technology may be new or untested, potentially providing the project manager with a complex situation to evaluate.

A critical issue associated with using new technology is the uncertainty associated with the untested technology. This uncertainty can be present in terms of the ability of the technology to succeed and also the time needed to implement the new technology. Hence, before beginning a project it is necessary that companies are able to estimate the cost of implementing a new technology in terms of the resources, delays and budget. It is also necessary that companies develop a contingency plan in the case that the new technology does not work as intended. Making the decision to go ahead with a new or untested technology, which may save a lot of effort, time, and money if it succeeds, could also cost a lot to companies if the technology fails. A contingency plan could be to repeat the same uncertain technology again or to use an alternative technology which is tested and has a higher probability of success or is sure to succeed.

The decision to adopt a new technology is based on various factors like probability to succeed (Creemers et al., 2009), estimated time to complete the project using a new technology, and the contingency plan or the backup plan if the new technology fails. This scenario may also arise in situations where more than one alternate technology may be available (not necessarily a new or untested technology) to implement the project and each alternate technology may have a different probability of success, associated costs and time. Selection of technology also depends on the

resources that are needed to implement the given technology, as there may be some parallel activities requiring the same set of limited resources.
The objective of this paper is to develop methodology for selecting from among several alternatives for completing project activities considering uncertainty in completion time and uncertainty in the reliability of the alternative for successfully completing the activities in order to minimize the expected completion time of the project. We present a stochastic simulation based optimization approach to help project planners make these decisions before the commencement of project.

This remainder of this paper is organized as follows, section two covers the overview of the related work and section three discusses the methodology and demonstrates the implementation through the use of an example. In section four we provide a discussion followed by the conclusions and future work in section five.

2. Literature Review

Simulation has been widely used in the field of project management for evaluating project crashing techniques, to evaluate alternate technologies, Simulating project networks, Risk management, Project management training, Project quality management systems, Project planning, Work force planning in software industry, Project costing, Resource management, Conflict management, Multi project management using dynamic programming. For example Haga and Marold (2004) discuss a two-step simulation based approach to crash the projects considering the uncertainty in project completion time, bottlenecks and a linear penalty function. Kuhl and Tolentino-Pena (2008) have also developed a dynamic approach for project crashing using simulation to evaluate the project at the beginning and also as the project progresses to reevaluate the strategy based on the penalty costs and the crash costs.

Time/cost tradeoffs of selecting a particular technology for implementation have also been studied widely. Some of these issues have also been dealt with in the risk management of projects. Issues related to selecting appropriate technologies have been dealt in different ways, for example, Frankel (1992) studied the problem of selecting alternate technologies and operational strategies in the shipbuilding industry using an analytic hierarchy process (AHP). This is a pairwise comparison of different alternatives, based on objectives such as quality, cost, time etc. They have also considered a stochastic approach of comparing various alternatives where, instead of assigning definite weights in the AHP tables a probabilistic assignment is considered. However, this approach does not consider each activity from the perspective of the entire project and it also does not consider the contingency plan that may be needed if the selected alternative fails. Johnson (2009) has discussed this problem from the point of view of assessment methods that could be used to evaluate the design or a technology being developed and its effect on the project lead time and costs. Author has developed a case study considering different assessment methods for evaluating the design and used Monte Carlo simulation to estimate the time and probability of success of each assessment method to evaluate impact on the project lead time and cost.

Liu et al. (1995) have studied the problem of selection of crew size, equipment and technology for the execution of a construction project. They have developed a hybrid LP/IP approach to optimize the resource allocation to control time and costs of the project. Linear program is initially used to establish lower limit for project time cost relationship and then the integer programming approach is used to select the most feasible option.

Creemers et al. (2009) studied this problem from the perspective of research and development projects. They have used backward dynamic programming recursion in a Markov decision chain to solve a stochastic problem associated with the selection of alternate technology, where each alternative has a probability to success and time uncertainty associated with a given technology with an objective to optimize the returns. The authors have not included availability of resources in their algorithm which may be another reason causing a delay in the project. However, unlike the Frankel (1992) this approach does consider a precedence relationship in the overall project.

Ranjbar and Davari (2013) also studied alternate technology projects in the research and development field. They have developed a branch and bound algorithm to schedule different alternatives that are available with an objective to reduce the time required for the development and maximizing the net present value. Even though the authors have considered parallel and sequential scheduling of each alternative they do not consider the availability of resources and uncertainty associated with time while scheduling the activities. In the projects related to Research and Development a project is considered to be successful even if one of the alternative succeeds and all the other activities that are in progress are stopped and also they do not consider the unavailability of resources, variation in time.

Mukherjee et al. (2009) use situational simulation in interactive, context-sensitive, adaptive environments. They further construction research by providing an interactive simulation platform that can be used to explore what-if construction scenarios and to estimate risks and contingencies. This paper proposes using querying algorithm to develop situational simulations in construction management. The main objective system is to enhance project management by providing the ability to flexibly input the simulation parameters such as event probabilities, to explore "what-if" scenarios, and to assess the sensitivity of final project outcomes to alternative decisions. This paper integrates the ability of situational simulations to be used as a risk assessment tool and an experimental test bed for assessing alternative decisions under risk and uncertainty.

Marmier et al. (2014) have developed a methodology to take strategic decision making in New Product Development initiatives. Authors consider effects of risk associated with time and cost. The authors use decision trees to evaluate risk associated with selecting a technology and they also consider the availability of skilled resources while making this decision. Cho and Eppinger (2005) use simulation technique to manage complex projects. The model computes the probability distribution of lead time in a stochastic, resource-constrained project network where iterations take place among sequential, parallel, and overlapped tasks. The model uses the design structure matrix representation to capture the information flows between tasks. A heuristic approach is used for stochastic, resource-constrained project scheduling problem in an iterative project network. The proposed model can be used to select project alternatives based on the time benefit analysis. Authors have presented a case study to understand the implementation of the proposed framework. Bayraktar and Hastak (2009) uses Bayesian belief networks to model the interdependencies between various factors that affect highway projects. The Project has certain targets and Bayesian belief network is used to calculate the probability of achieving the target based on the alternative selected. Monte Carlo simulation is used to determine the impact of each decision on the target value to select the best possible alternative.

3. Methodology

In this section, we develop a stochastic simulation based methodology to evaluate the use of alternate or new technologies in a project where activity completion times and reliability of the alternatives may be stochastic. This research intends to answer following questions:

- Which combination of activity completion alternatives and corresponding contingency alternatives should be selected in order to minimize the time required to complete the project successfully?
- What are the expected project performance measure values for the optimal configuration including the criticality indices and expected project completion time?

The methodology we propose to solve this class of problem is represented in the Figure 1.

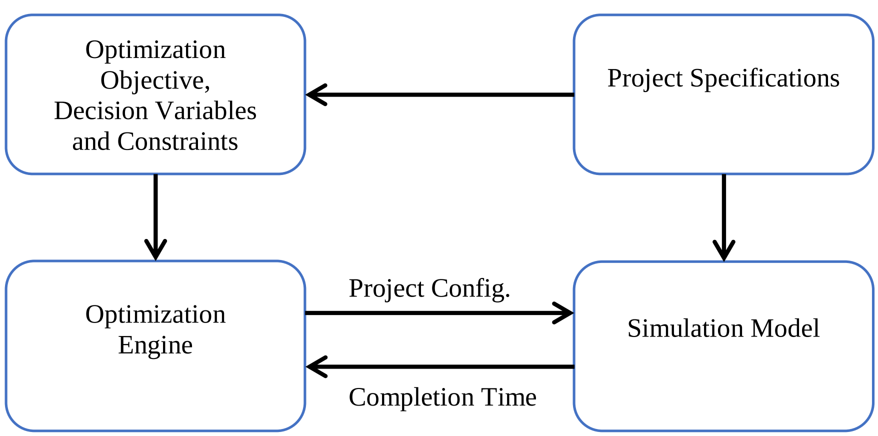


Figure 1: Simulation-based optimization methodology

The project specification includes all of the project activities and their precedence relationships. Each activity in a project network is characterized by the time needed to complete the activity, resources needed for the activity, alternate technologies available for the activity and probability of success of each technology. Further, except for the resources, there may be uncertainty associated with each of the above mentioned parameters needed for the successful completion of a project. It is necessary to consider these uncertainties during the planning stage of the project so that appropriate alternatives can be selected keeping in mind the final objective. This methodology is designed to evaluate a technology alternative which will result in a successful project. While evaluating this alternative, all the uncertainty associated with the activity duration and the probability of success is considered.

For the case of activities with one or more alternatives having a probability of success less than one, a contingency plan (rule) is needed for the case(s) where the initial alternative may fail. The contingency could be to utilize a reliable (probability of success equal to 1) alternative as a backup to the unreliable alternative. Another approach may be to repeat the selected alternative a specified number of times until either the activity is completed successfully or a reliable alternative is to be applied. The specification of an appropriate contingency plan will often be determined by the project application.

Given a project specification, a simulation-based optimization framework has been designed to generate an optimal combination of alternatives that will minimize the time required for completing the project. A discrete-event simulation model is used to represent the dynamic behavior of the project network and enforce the precedence relationships of the alternatives. The simulation model is constructed so that one replication of the simulation model represents one complete execution of the project. An activity can begin only if its predecessor activities have been completed, and the resources to complete that activity are available. When an activity starts, the time required for that activity is sampled from the specified activity duration distribution. This process continues until all activities have been completed. Finally, the performance measures of the system including the critical path and project completion time are reported.

To evaluate alternative system configurations, the simulation model is integrated with an optimization engine. The input to the optimization engine includes the objective function which in this case is to minimize expected project completion time. The decision variables for the optimization include the primary alternative for each of the activities with multiple alternatives to select from among (some of which may be unreliable), as well as the alternative to be used as the contingency in the case the primary alternative fails. Constraints may also be specified to limit the optimization engine to a feasible combination of alternatives.

When executing the optimization, the optimization engine supplies the simulation model with a project configuration that includes the set of primary and contingency alternatives to be evaluated. The simulation model is then run with the specified project configuration and returns the resulting simulated project completion time. The process of evaluating potential project configurations continues until the optimal configuration is identified. The methodology determines the best possible alternatives to select, contingency plan for each of the selected alternatives along with the criticality index of each activity and expected project completion time.

In the next section, we discuss the implementation of the methodology in the context of an illustrative example.

3.1 Implementation

The methodology is implemented using a commercial simulation software package, SIMIO, which includes a simulation-based optimization engine, OptQuest, as well as a framework for setting up and running experiments. We will utilize the following example (based on Nazrul and Sharif, n.d.) to illustrate the implementation of the methodology.

Example: *Consider a project consisting of 12 activities having stochastic completion times where two of the activities, Activity 3 and Activity 11, each have four alternative methods to select from among to complete that activity. Of these alternatives, one is reliable with a likelihood of successful completion equal to 1, and the other three have varying degrees of likelihood of successful completion. The project network is displayed in Figure 2, and the details associated with the completion of each activity are shown in Table 1. For this project, we would like to determine the primary and contingency alternatives to select for activities 3 and 11 that will minimize the expected completion time of the project.*

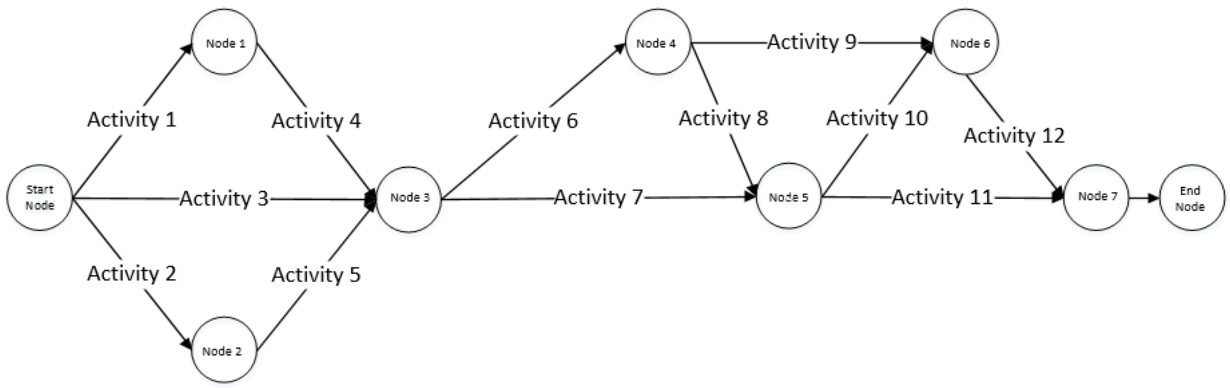


Figure 2: Example project network (Activity On Arc)

Table 1: Example Project Data

Activity	Number of Options	Option	Time (Days) (Min., Mode, Max.)	Probability of Success	Resource Type	Predecessor Activities
1	1	1	8,10,12	1.0	C	-
2	1	1	6,7,9	1.0	B	-
3	4	1	3,4,5	0.7	G	-
		2	4,5,6	0.5	H	
		3	3,3,4	0.6	I	
		4	9,11,12	1.0	F	
4	1	1	8,9,10	1.0	C	1
5	1	1	6,7,8	1.0	D	2
6	1	1	9,10,11	1.0	F	3,4,5
7	1	1	6,7,10	1.0	E	3,4,5
8	1	1	14,15,16	1.0	B	6
9	1	1	10,11,13	1.0	A	6
10	1	1	6,7,8	1.0	D	7,8
11	4	1	5,7,8	0.5	J	7,8
		2	4,7,8	0.8	K	
		3	3,7,8	0.5	L	
		4	10,11,12	1.0	F	
12	1	1	1,2,4	1.0	C	9,10

To implement the methodology, the first step is to create a simulation modeling framework to allow for the efficient representation of project networks that will facilitate the process of optimization and experimentation. The basic network structure based on the SIMIO objects to represent nodes and activity arcs developed by Joines and Roberts (2010) which they refer to as junctions and project time paths, respectively.

To represent activities that have alternative unreliable technologies with a contingency alternative, we developed a new sub-class object in SIMIO called “prjtimepath_withoptions”. In order to make “prjtimepath_withoptions” flexible to work with and array of project configurations, we utilize a data table. One of the highlights of this model is that, we do preprocessing of the alternatives before the beginning of each activity i.e. at the beginning of each activity the simulation model will go through the data defined for the alternative technologies, where we sample through the distribution function for the activity duration, probability of success, seize and release resources required for each alternative and keep track of the time elapsed. Once the model finds the successful technology, the project activity will be executed. The model is flexible enough to define the number of iterations that the simulation should repeat if the unreliable activity is to be tried multiple times. For example, we can set it in such a way that if a particular alternative fails, then it will immediately select an alternative which will definitely succeed or we can test different combination of alternatives. We can set a limit on the number of iterations to eliminate any issues associated with looping if a particular alternative fails repeatedly. Figure 3 displays implemented simulation model for the example project network.

In order to provide a flexible means of specifying the input data for the project activities and their respective alternatives, we utilize a data table. The data table containing the input data for the example project network is shown in Figure 4. The first two columns of the table identify the activity number and the number of alternatives (options) for completing the activity, respectively. The third column, *Option*, contains a unique option number within each activity. The column labeled *Time (Days)* contains the distribution of activity completion time for the corresponding option. The column labeled *Probability_of_Success* provides the distribution from which the probability of successfully completing the activity utilizing corresponding alternative is sampled. In this example, we utilize a discrete distribution for unreliable alternatives and a constant value of 1 for reliable alternatives. Finally, the last column indicates the name of the resource needed to perform the corresponding alternative for each activity. Another advantage of utilizing a data table is that data from various scenarios can be created and/or stored in spreadsheet and copied into the data table to execute experiments.

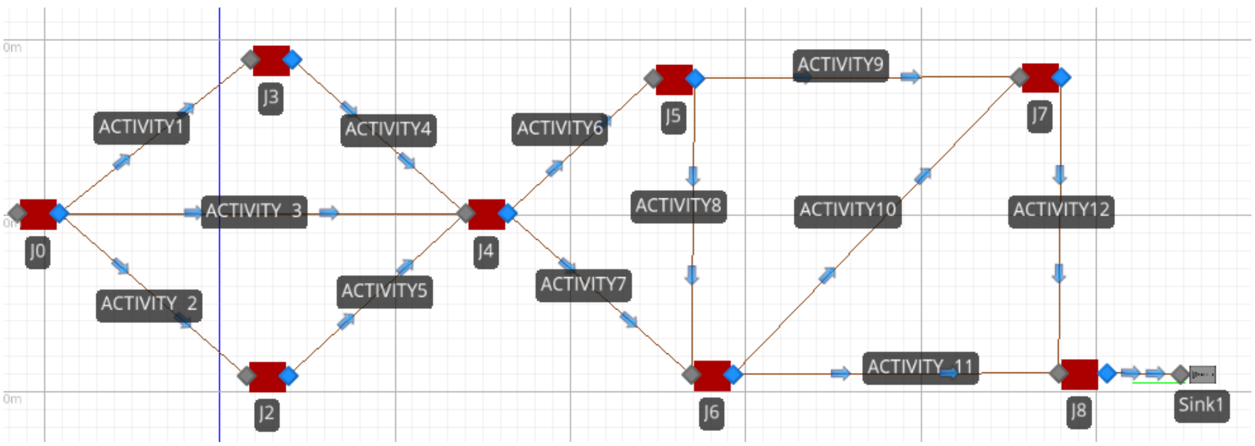


Figure 2: Implementation of example project network

	Activity	num_options	option	Time (Days)	Probability_of_Succees	Resource
1	1	1	1	Random.pert(8,10,12)	1	ResourceC
2	2	1	1	Random.pert(6,7,9)	1	ResourceB
3	3	4	1	Random.pert(3,4,5)	random.discrete(0,0.3,1,1)	ResourceG
4	3	4	2	Random.pert(4,5,6)	random.discrete(0,0.5,1,1)	ResourceH
5	3	4	3	Random.pert(3,3,4)	random.discrete(0,0.4,1,1)	ResourceI
6	3	4	4	Random.pert(9,11,12)	1	ResourceF
7	4	1	1	Random.pert(8,9,10)	1	ResourceC
8	5	1	1	Random.pert(6,7,8)	1	ResourceD
9	6	1	1	Random.pert(9,10,11)	1	ResourceF
10	7	1	1	Random.pert(6,7,10)	1	ResourceE
11	8	1	1	Random.pert(14,15,16)	1	ResourceB
12	9	1	1	Random.pert(10,11,13)	1	ResourceA
13	10	1	1	Random.pert(6,7,8)	1	ResourceD
14	11	4	1	Random.pert(5,7,8)	random.discrete(0,0.5,1,1)	ResourceJ
15	11	4	2	Random.pert(4,7,8)	random.discrete(0,0.2,1,1)	ResourceK
16	11	4	3	Random.pert(3,7,8)	random.discrete(0,0.5,1,1)	ResourceL
17	11	4	4	Random.pert(10,11,12)	1	ResourceF
18	12	1	1	Random.pert(1,2,4)	1	ResourceC

Figure 4: Data table for example project network

Once the simulation model has been constructed, the optimization experiment is set up. Due to the use of data tables, the decision variable used in the optimization simply correspond to the primary and back up options for activities with multiple alternatives. The response variable is set up to reflect the performance measure that the use would like to optimize such as completion time or cost. In this example, we apply the simulation-based optimization method to the project network with the alternative options for activities 3 and 11 with an objective of minimizing the time required for completing the project. In this particular example, we have selected the reliable alternative to be the contingency option in the case that the primary unreliable alternative is not successful at completing the activity. As each activity has three unreliable options and one reliable option, there are 16 total possible scenarios which have been considered for experimentation. Table 3 shows the details of the experimental results. For this example, each of the 16 scenarios were run for 1500 replication (i.e. 1500 sample project instances).

Table 3: Project completion time for different combinations

Scenario	**Activity 3**	**Activity 11**	**Average (Days)**	**SD (Days)**	**95% CI Half-Width**
	Primary* / *Back up	***Primary* / *Back up***			
1	2 / 4	2 / 4	54.71	3.57	0.20
2	3 / 4	2 / 4	54.80	3.58	0.20
3	1 / 4	2 / 4	54.81	3.62	0.21
4	4 / -	2 / 4	54.81	3.64	0.15
5	4 / -	4 / -	54.96	1.07	0.06
6	3 / 4	4 / -	54.98	1.07	0.05
7	1 / 4	4 / -	55.00	1.06	0.05
8	2 / 4	4 / -	55.00	1.06	0.05
9	3 / 4	3 / 4	57.28	4.36	0.25
10	1 / 4	3 / 4	57.37	4.40	0.25
11	2 / 4	3 / 4	57.39	4.43	0.25
12	3 / 4	1 / 4	57.45	4.49	0.26
13	4 / -	3 / 4	57.45	4.37	0.19
14	1 / 4	1 / 4	57.53	4.52	0.26
15	2 / 4	1 / 4	57.55	4.56	0.26
16	4 / -	1 / 4	57.59	4.49	0.19

3.2 Analysis of Results

The results shown in Table 3 have been ordered by increasing average project completion time. The scenarios were then numbered from 1 to 16 to facilitate this discussion. In comparing the average completion time across scenarios, one observes that first 8 scenarios result values that are not statistically significantly different from one another. However, it does appear that utilizing option 2 or 4 as the primary option for Activity 11 results in a lower average time than utilizing the other options.

In addition to the average project completion time, it is also interesting to observe how the critical path changes under the various scenarios. In Table 4, we present the slack time and criticality index for each of the activities under the first 5 scenarios. Note that Scenario 5 is the scenario where both Activity 3 and Activity 11 utilize the reliable option to perform the task. In Scenario 5, Activity 11 is on the critical path 99% of the time while it is reduced to less than 20 percent in the other four scenarios. Activity 3 on the other hand is never on the critical path in any of the scenarios, but one can observe the changes in slack time across the five scenarios.

To further analyze the resulting behavior under various scenarios, we can observe the distribution of the resulting project completion times. From Table 3 we can observe that when unreliable alternatives are used, the standard deviation of the project completion time increases. The reason for this is the fact that when the primary option is unreliable, the distribution of project completion time tends to be bimodal in nature. The first mode occurs when the primary option is successful, and the second mode occurs when both the primary option and secondary option are required because the primary option failed. In general, with this type of situation, the distribution will be multimodal depending on the number of activities having unreliable primary options. Figure 5 displays the empirical cumulative distribution functions for each of the sixteen scenarios. Furthermore, the empirical density functions for Scenario 1 and Scenario 5 are displayed in Figure 6 along with a comparison of their empirical cumulative distribution functions. Here one can observe that Scenario 1 has a high likelihood of reducing the overall project completion time if the primary option for Activity 11 is successful, however, if not, the resulting completion time will be slightly higher than if the reliable option was selected.

Table 4: Slack and critical path values for example project

	Scenario 1		**Scenario 2**		**Scenario 3**		**Scenario 4**		**Scenario 5**	
Act. 3	**2 / 4**		**3 / 4**		**1 / 4**		**4 / -**		**4 / -**	
Act. 11	**2 / 4**		**2 / 4**		**2 / 4**		**2 / -**		**4 / -**	
Activity	*Slack (Days)*	*Critical Path*	*Slack (Days)*	*Critical Path*	*Slack (Days)*	*Critical Path*	*Slack (Days)*	*Critical Path*	*Slack (Days)*	*Critical Path*
1	0.00	1	0.00	1	0.00	1	0	1	0.00	1
2	0.00	1	0.00	1	0.00	1	0	1	0.00	1
3	**8.26**	**0**	**11.30**	**0**	**11.70**	**0**	**8.17**	**0**	**8.16**	**0**
4	0.00	1	0.00	1	0.00	1	0	1	0.00	1
5	4.85	0	4.80	0	4.84	0	4.86	0	4.85	0
6	0.00	1	0.00	1	0.00	1	0	1	0.00	1
7	17.69	0	17.71	0	17.70	0	17.6	0	17.61	0
8	0.00	1	0.00	1	0.00	1	0	1	0.00	1
9	10.80	0	10.82	0	10.83	0	10.8	0	10.83	0
10	0.00	1	0.00	1	0.00	1	0	1	0.00	1
11	**2.03**	**0.18**	**2.08**	**0.19**	**1.99**	**0.19**	**1.98**	**0.19**	**0.00**	**0.99**
12	1.58	0.82	1.62	0.81	1.66	0.81	1.66	0.8	1.85	0.01

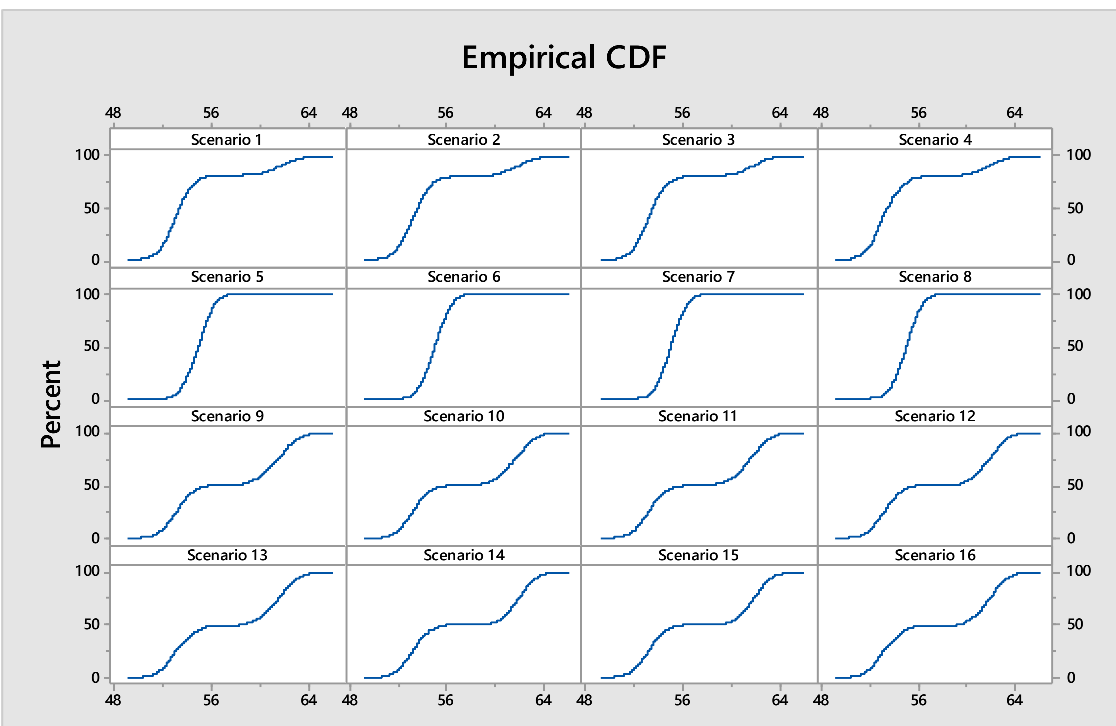
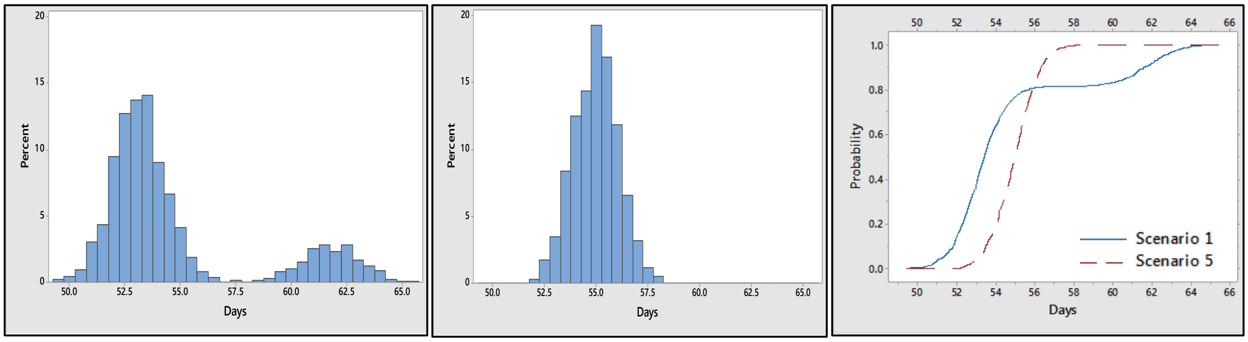


Figure 5: Empirical cumulative distribution of project completion time for each of the scenarios



(a) (b) (c)

Figure 6: Comparison of the distribution of project completion time (a) Scenario 1 empirical density; (b) Scenario 5 empirical density; and (c) empirical cumulative distributions of project completion time

4. Discussion

In the example that we have considered, there is no benefit in terms of the project completion time if we consider alternate technologies for Activity 3. Since Activity 3 is never on the critical path hence, even if we use alternate technology with shorter duration it won't affect the duration of the project. However, using an alternate technology does have an impact on the expected slack time for the activity. This increased slack time means that additional time that is freed up could be used for productive work on this or other projects. In addition, the company may feel that since Activity 3 is not on the critical path trying one of the alternative methods may be beneficial in terms of gaining experience with the methods for future projects. In the case of activity 11, the method that we have used clearly shows that using an alternate technology will affect the criticality index of this activity. In addition, given the distribution graphs, one could better judge for the particular project under consideration whether the potential benefit be worth the risk of additional time that may result if the alternative technology is not successful.

5. Conclusions

We have developed and implemented a simulation-based optimization method to evaluate project networks and evaluate strategies with respect to selection of alternate technologies when the alternatives may be unreliable. This method uses an optimization framework based on a stochastic simulation model to determine the appropriate combinations of options and contingency plans for the project. This methodology for analyzing alternate technologies for the project activities has shown promising results by identifying the effects of using new technologies on the project duration and criticality index of the activities. However, in order to further improve this methodology future work will include rigorous testing of the model to consider the effects of resource conflicts on the project duration and also to include the costs of using alternate technologies in make decisions for using alternate technologies and determining contingency plans.

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